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The work performed in the reporting period has been focused on completion of Task 1.1, and continuation of Task 1.2 and Task 2.2 described in the project proposal. The activities related to Task 1.1 are formation of cracks in a computational micromechanics failure analysis of a representative volume element containing disordered fiber distributions and Task 1.2 concerns growth and instability of initiated cracks in the environment of the disordered fiber distributions. The activities related to Task 2 cover modeling of interface bonds between different phases in a composite.

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A Hybrid Approach to Composite Damage and Failure Analysis Combining Synergistic Damage Mechanics and Peridynamics

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Executive Summary

The work performed in the reporting period has been focused on completion of Task 1.1, and continuation of Task 1.2 and Task 2.2 described in the project proposal. The activities related to Task 1.1 are formation of cracks in a computational micromechanics failure analysis of a representative volume element containing disordered fiber distributions and Task 1.2 concerns growth and instability of initiated cracks in the environment of the disordered fiber distributions. The activities related to Task 2 cover modeling of interface bonds between different phases in a composite.

Task 1.2 Ply level constrained cracking

Task 1.1 dealt with initiation of micro-level cracking. It has been essentially completed and most results were reported in previous quarterly reports. Figure 1 illustrates the process of crack initiation from clustering of cavitation points in the matrix. On the left is the representative volume element (RVE) consisting of nonuniformly distributed fibers embedded as a circular cell within the homogenized composite of outer rectangular boundary. The assembly is subjected to a uniform displacement normal to the fiber axis. From the stress and strain fields calculated by a finite element model (left in Fig. 1), and application of a criterion for cavitation in the matrix, the first and subsequent points of dilatation induced cavitation are found. Two stages of the evolution of cavitation are shown in Fig. 1. In the early stage (middle figure), diffuse points of cavitation occur, while clustering of the cavitation occurs as the applied transverse tension increases.
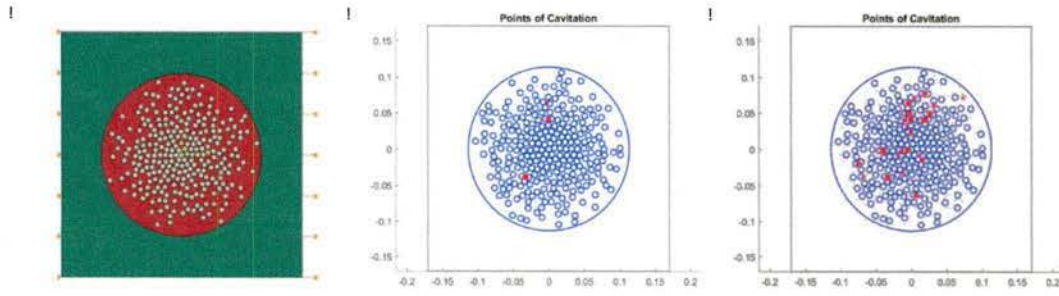
Figure 1. The RVE consisting of discrete disordered fiber distribution is embedded as a circular cell within a homogenized composite region (left) and the assembly is subjected to uniform tension. The figure in the middle shows early stage of cavitation and the one to the right shows a later stage. Red dots indicate the points where cavitation occurs under transverse tension.

Multiple realizations of RVEs are generated and for each realization representing a certain degree of fiber mobility during the manufacturing process, the formation of the first crack is studied. The criterion for crack formation is occurrence of ~4 cavitations along a strip oriented approximately normal to the loading direction. Each cavitation is assumed to cause fiber/matrix debonding, as described in previous reports. Coalescence of the adjacent disbonds results in initiation of a transverse crack. Figure 2 (a) plots the applied strain at which first cavitation occurs and when the first crack forms. The results are plotted against increasing mobility of fibers given by the radial deviation from initial positions in the dry bundle state.
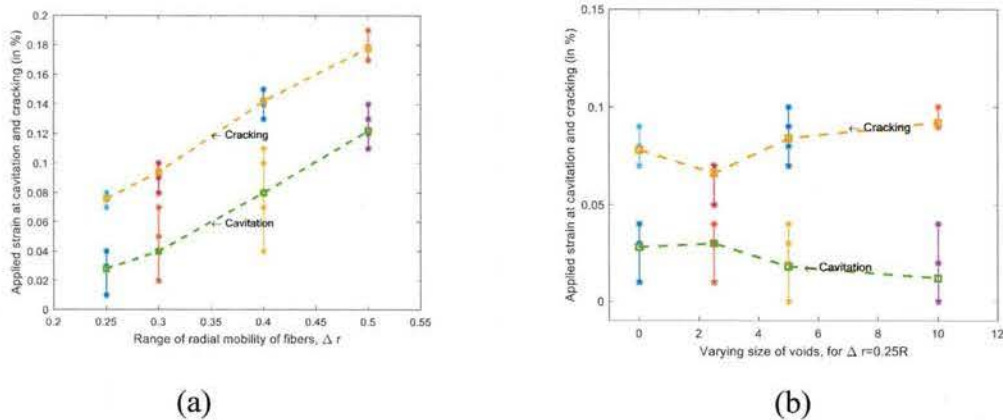

(a) (b)

Figure 2. (a): The applied strain at which transverse cracking occurs and at which the first cavitation causing fiber/matrix debonding occurs versus the radial mobility of fibers during the resin infusion process (for a fixed angular mobility). (b): The same strains as in (a) when voids of different size are present at one fiber mobility.

The failure analysis described above is conducted with micro-voids present between the fibers. The results for one case of fiber mobility (i.e., one case of fiber clustering) are plotted in Fig. 2(b). The results suggest that generally, the strain to crack formation is higher by approximately the same amount at all void sizes. These strains increase with fiber mobility, i.e. with reduced fiber clusters. However, when micro-voids are present, the effect is to cause cavitation as well as crack formation earlier.

The ongoing research will focus on continued growth of the initiated transverse cracks. Conditions for instability of crack growth will be examined.

Task 2. Peridynamic modeling of failure at the interface between composite phases

Background

Lead-free solder joints used in microelectronics and electronic packaging for critical mission defense applications tend to fail because of the presence of intermetallic compounds in the solder matrix material. In Figure 3 (a) we show an example of a failed solder joint from repeated drop-tests. The fractures tend to happen along the intermetallic component or at the interface between the two components of the composite. The availability of microscale experimental data in these systems make them a good choice for testing the peridynamic modeling of failure in composites.
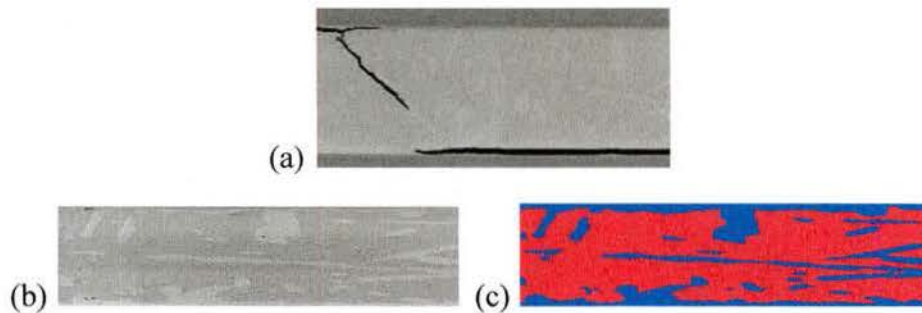

Figure 3. (a) Microscale SEM image of a failed solder joint; (b) selection of a sample microstructure to be used for modeling; (c) the digitized material map for the microstructure in (b).

Approach and Results

To this end, we create a digitized model of the two-phase composite (see Figure 3b and 3c), in which the blue phase is the brittle phase. The properties of the bonds between peridynamic nodes in the matrix (SAC305) and the inclusions (AuSn4) are calibrated to their respective composition, while for the bonds that cross material interfaces between these two components, we use interface bonds (see Figure 4). The properties of these bonds are based on a "mixture" of the properties of the individual phases.
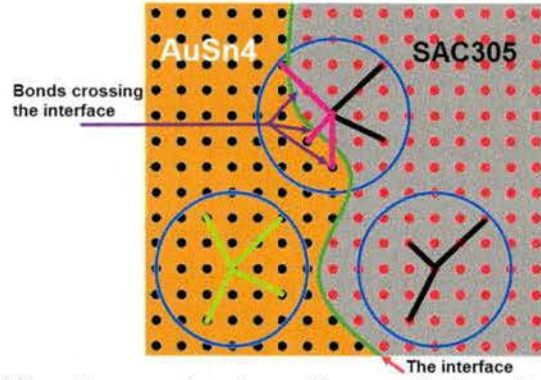
Figure 4. Assignment of bond properties depending on the location of its end-nodes. Interface bonds have special properties.

Using boundary data from time-series of component-level finite element simulations, the peridynamic results show growth of cracks that propagate mostly along the material interfaces between the inclusions and the matrix (se Figures 5a and 5b).
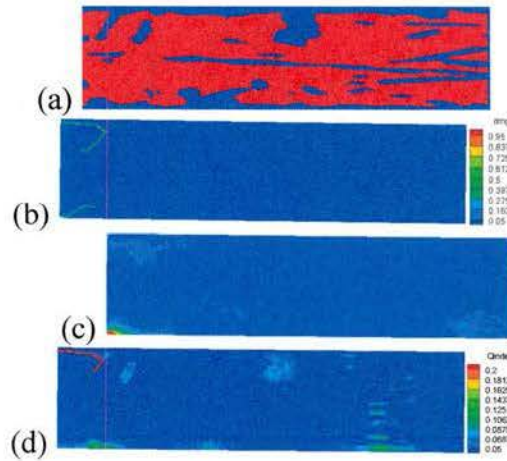

Figure 5. (a) the digitized composite sample; (b) damage index map showing the presence of two main crack lines obtained with the PD model; (c) map of strain energy density; (d) the new quasi-index damage is a predictor of failure.

As in the case of FRCs, one wants to primarily increase reliability of electronic components and avoid failure. The strain energy density, in a homogeneous material, is a good measure for estimating the propensity of failure at a point. However, for composite materials, the strain energy density is no longer a good indicator of where failure might occur (see Figure 5c). This is why we introduced a new measure, a precursor of fracture, which can give an indication of which points are most likely to fail, before actual failure happens. The "quasi-damage index", shown in the formula below, is a point-wise measure that uses the strain in a bond between nodes i and j, the total number of bonds at the node x_i, $N(x_i)$, and $s_0(i,j)$, the critical strain for bond (i,j).

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$$Q(x_i) = \frac{1}{N(x_i)} \sum_{j=1}^{N(x_i)} \min\left(\frac{s(i,j)}{s_0(i,j)}, 1\right)$$

With the quasi-damage index, we are able to foresee where the cracks may initiate from. The comparison between Figures 5b and 5d prove this point.

The ongoing research will extend this approach to investigate failure in fiber-reinforced composites. The draft for a journal paper on the topic shown above is in preparation.